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ON DEEP-OCEAN ^{60}Fe AS A FOSSIL OF A NEAR-EARTH SUPERNOVA

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ABSTRACT

Live ^{60}Fe has recently been reported in a deep-ocean ferromanganese crust. Analysis of the isotopic ratios in the sample suggests that the measured ^{60}Fe abundance exceeds the levels generated by terrestrial and cosmogenic sources, and it has been proposed that the excess of ^{60}Fe is a signature of a supernova that exploded near the earth several Myr ago. In this paper, we consider the possible background sources, and confirm that the measured ^{60}Fe is significantly higher than all known backgrounds, in contrast with the reported abundance of live ^{53}Mn in the same sample. We discuss scenarios in which the data are consistent with a supernova event at a distance $D \sim 30\,\mathrm{pc}$ and an epoch $t_{\rm SN} \sim 5\,\mathrm{Myr}$ ago. We propose tests that could confirm or refute the interpretation of the ^{60}Fe discovery, including searches for ^{10}Be, ^{129}I and ^{146}Sm. Such a nearby supernova event might have had some impact on the earth's biosphere, principally by enhancing the cosmic-ray flux. This might have damaged the earth's ozone layer, enhancing the penetration of solar ultraviolet radiation. In this connection, we comment on the Middle Miocene and Pliocene mini-extinction events. We also speculate on the possibility of a supernova-induced "cosmic-ray winter", if cosmic rays play a significant role in seeding cloud formation.

Subject headings: supernovae — nuclear reactions, nucleosynthesis: abundances

1. Introduction

The literature contains considerable discussion of the likelihood of nearby supernova events: their frequency has been estimated (Shklovsky 1968), and their possible impacts on the biosphere have been considered (Ruderman 1974; Ellis & Schramm 1995; Ellis, Fields, & Schramm 1996).

Within the considerable uncertainties, it is conceivable that there may have been one or more nearby supernova events during the Phanerozoic era. This has prompted discussion of their isotopic signatures and kill radii, and speculation on their possible role in triggering biological mass extinctions.

Supernova events that were sufficiently close to have left some terrestrial isotope signature, but far enough not to have triggered a mass extinction, are expected to have been more frequent. In this connection, various authors have noted the enhancement of ^{10}Be in ice cores and marine sediments ~ 35 kyr BP (BP = before the present). In particular, Ellis, Fields, & Schramm (1996) discussed the possibility that this might have arisen from the supernova event that gave birth to the Geminga pulsar, and proposed looking at deep-ocean sediments, suggesting that the long-lived isotopes ^{129}I, ^{146}Sm, and ^{244}Pu, as well as the shorter-lived ^{10}Be, ^{26}Al, ^{36}Cl, ^{53}Mn, ^{60}Fe, and ^{59}Ni, might provide geological evidence of a nearby supernova event at any time during the past 10^8 yr or more.

In the light of this proposal, the recent deep-ocean ferromanganese crust measurements (Knie et al. 1998) of ^{60}Fe ($t_{1/2} = 1.5$ Myr) and ^{53}Mn ($t_{1/2} = 3.7$ Myr) are very exciting. Whilst ^{53}Mn is known to have a significant natural background from interplanetary dust accretion, the expected background for ^{60}Fe is significantly lower than the measured levels. Knie et al. discuss possible alternative origins for the apparent excess of ^{60}Fe, and argue that their results can only be understood in terms of a supernova origin for the ^{60}Fe. As we discuss in more detail later, their data suggest a nearby supernova event within ~ 30 pc during the past few Myr, a significantly longer timescale than had been discussed in connection with the ^{10}Be signal.

The data are very new and the statistics is small, with only 63 ^{60}Fe and ^{53}Mn nuclei being detected in total. However, if these data are confirmed, together with their extraterrestrial interpretation, the implications are profound. The would constitute the first direct evidence that a supernova event occurred near earth within a relatively recent geological time, with detectable effects on our planet. The purpose of this paper is to discuss the implications of the data in more detail.

We first re-estimate the cosmogenic backgrounds to both the ^{60}Fe and ^{53}Mn signals observed by Knie et al. (1998). We confirm their estimates that the ^{60}Fe signal is higher than plausible cosmogenic sources, whereas the ^{53}Mn signal is compatible with such backgrounds. We emphasize the desirability of understanding better the sedimentation history of the last 20 Myr, and seeking confirmation in other ferromanganese crusts and elsewhere that the apparent ^{60}Fe excess is global. We stress in particular the desirability of finding an earlier layer in which the apparent ^{60}Fe excess is absent. We then use the available data to derive constraints on the possible supernova event, including its time and distance. We also discuss the possible implications for supernova nucleosynthesis and review other isotope signals - such as ^{10}Be, ^{129}I and ^{146}Sm - that could be used to confirm the supernova diagnosis and deepen its interpretation. Finally, we address the possible implications of this apparent supernova event for the terrestrial biosphere. We revisit the effects of the expected cosmic-ray flux on the earth's ozone layer, and the resulting enhanced penetration of the atmosphere by solar ultraviolet radiation. We speculate whether its effects could be related to either of the mini-extinctions that apparently occurred during the Middle Miocene and Pliocene epochs. We also raise the possibility of other supernova-induced effects on the biosphere, in particular the possibility that the enhanced cosmic-ray flux might seed extra cloud cover, potentially triggering global cooling: a "cosmic-ray winter".

2. Data

Knie et al. (1998) studied the isotopic composition of a deep ocean sample of hydrogenic ferromanganese crust. This is material which has slowly precipitated from seawater onto one of several specific kinds of substrate. Using accelerator mass spectrometry, Knie et al. detected both live ^{60}Fe and live ^{53}Mn in three layers at different depths, spanning 0 to 20 mm. They estimate that these depths correspond to times spanning 0 to 13.4 Myr BP. Their data are summarized below. From the outset of our analysis, we emphasize caution, since the data may yet turn out to be a false alarm. We re-analyze the consistency of the data with conventional cosmogenic backgrounds before exploring the consequences if their interpretation in terms of a nearby supernova explosion is confirmed. We emphasize the necessity for follow-up data to confirm or reject this tantalizing scenario.

Table 1: Ferromanganese crust data from Knie et al. (1998).

depth mm	age Δt_ℓ Myr BP	^{53}Mn events	$\phi_{53}(\Delta t_\ell)$ cm^{-2} Myr^{-1}	$N_{53}(\Delta t_\ell)$ cm^{-2}	^{60}Fe events	$\phi_{60}(\Delta t_\ell)$ cm^{-2} Myr^{-1}	$N_{60}(\Delta t_\ell)$ cm^{-2}
$0-3$	$0-2.8$	26	2.6×10^8	5.7×10^8	14	1×10^6	1.6×10^6
$5-10$	$3.7-5.9$	6	6.4×10^8	5.8×10^8	7	7×10^6	1.8×10^6
$10-20$	$5.9-13.4$	7	4.4×10^8	6.0×10^8	2	9×10^6	1.3×10^6

Knie et al. quantify their detection in terms of the flux $\phi_i(\Delta t_\ell)$ deposited in layer ℓ of the crust, which they infer as follows. Using an independently determined crustal growth rate (which varies from $1-2\,\mathrm{mm\,Myr^{-1}}$), Knie et al. translate the depth of each layer into time intervals $\Delta t_\ell = (t_{\ell,\mathrm{i}}, t_{\ell,\mathrm{f}})$ before the present. The fluxes are calculated given the number of detected events in each layer, corrected for radioactive decays, and assuming a constant deposition during each time interval. The reported fluxes appear in Table 1. They found that the inferred fluxes of ^{60}Fe increase as one goes back in time, whereas the inferred fluxes of ^{53}Mn are less variable. Since both radioisotopes are found in all three layers, whereas a nearby supernova would naively be expected to have contaminated at most one layer, one might conclude that the background must be significant for both isotopes. However, as we discuss below, astrophysical effects might have spread out the deposition of the signal, and one should not ignore the possibility of some terrestrial mixing effect such as bioturbation. Knie et al. estimate that the ^{53}Mn background is large and do not use this as the primary indicator of a supernova signal. In §3.1, we explicitly calculate the expected background levels.

In our analysis below, we find it useful to express the observations in terms of the (present-day, uncorrected) surface density $N_i^{\rm obs}(\Delta t_\ell)$ detected in crust layer ℓ. To extract this from the reported fluxes one simply inverts the procedure used to derive the fluxes

$$N_i^{\rm obs}(\Delta t_\ell) = \int_{t_{\ell,\rm i}}^{t_{\ell,\rm f}} dt\ \phi_i(t)\ e^{-t/\tau_i} \quad (1)$$

$$= \left[\exp\left(-\frac{t_{\ell,\rm i}}{\tau_i}\right) - \exp\left(-\frac{t_{\ell,\rm f}}{\tau_i}\right)\right]\ \tau_i\ \phi_i(\Delta t_\ell) \quad (2)$$

The inferred surface densities also appear in Table 1. Note that, although the inferred flux is strongly varying with time, the present surface density is quite constant. We examine later reasons why the ^{60}Fe signal is seen in multiple crust layers, in apparent conflict with the simplest picture of punctuated deposition of material after a nearby supernova explosion.

As noted by Knie et al., the observed flux of material into the ferromanganese crust is not necessarily the same as the mean flux of material averaged over the globe. The largest difference between the two arises from the reduced uptake of both Mn and Fe into the crust, i.e., the efficiency for each of these elements to be deposited onto the crust is not perfect, and thus the flux onto the crusts is lower than the flux deposited over the earth's surface. Consequently, the surface densities in the crust and globally are related by

$$N_i^{\rm obs} = f_i\ N_i^{\oplus} \quad (3)$$

where $N_i^{\oplus}$ is the global surface density deposited, and $f_i < 1$ accounts for the reduced uptake. Thus, to compare with the observations, one must reduce the theoretically expected surface density, $N_i^{\oplus}$, by the uptake factor f_i in order to compare with the observations. In our calculations, we use the fiducial values suggested by Knie et al., who recommend approximate values of $f_{53} \sim 1/20$, and $f_{60} \sim f_{53}/5 \sim 1/100$, which are based in part on estimates of the ^{53}Mn background. We find that these estimates have significant uncertainties, which translate directly into corresponding uncertainties in f_{53}, f_{60}, and finally $N_{60}^{\oplus}$.

3. Interpreting ^{60}Fe in the Nearby Supernova Hypothesis

Ellis, Fields & Schramm (1996) estimated the terrestrial deposition of observable long-lived β-unstable nuclei. Since the deposition rate is a few mm Myr^{-1}, any radioisotopic signature should be temporally isolated, unless there is some astrophysical effect or disturbance of the deposited layers that could smear out the time resolution. However, even if that is the case, one can still constrain the deposited fluence F_i of the radioisotopes and the time since deposition. If one measures a surface density N_i of atoms per unit area, which was deposited at a time t before the present, one knows that then

$$N_i(t) = \frac{1}{4}\ F_i\ e^{-t/\tau_i} \tag{4}$$

where we assume that the fall-out on the earth's surface is isotropic, the factor of 1/4 is the ratio of the area of the earth's shadow ($\pi R_\oplus^2$) to the surface area of the earth ($4\pi R_\oplus^2$), and τ_i is the mean life of i. If one assumes an isotropic ejection of supernova debris, the deposited fluence is in turn directly related to the supernova distance D and the yield:

$$F_i = \frac{M_i/A_i m_p}{4\pi D^2} \tag{5}$$

where the mass ejected in species i is M_i. Note that we have assumed for simplicity that essentially no decays occur as the ejecta is transported to the earth, i.e., that the transit time $\delta t \ll \tau_i$. As we expect $\delta t \lesssim few \times 10^5$ yr for a supernova blast, this is an excellent approximation within the accuracy of our calculation. Combining (4) and (5), we have

$$\begin{aligned} N_i(t) &= \frac{M_i/A_i m_p}{16\pi D^2}\ e^{-t/\tau_i} \\ &= 4.6 \times 10^8\ e^{-t/\tau_i}\ \mathrm{cm}^{-2}\ \left(\frac{A_i}{60}\right)^{-1} \left(\frac{M_i}{10^{-5} M_\odot}\right) \left(\frac{D}{30\,\mathrm{pc}}\right)^{-2} \end{aligned} \tag{6}$$

We re-emphasize that the surface density calculated here assumes (1) an isotropic explosion, (2) isotropic fall-out on the earth's surface, and (3) that the incorporation of the debris into the crust or sediment that is sampled is faithful (i.e., no chemical fractionation and 100% uptake). The real situation is likely to violate all of these assumptions at some level. In particular, Knie et al. note that fractionation and reduced uptake effects have already been observed and are large. Such effects must be taken into account before one can use (6) to compare theory and observation.

If one can indeed deduce the supernova contribution to the abundance of *one* radioisotope in a sediment or crust, then one can determine the supernova distance with the addition of two other inputs. That is, with the observations $N_i^{\rm obs}$ in hand, one can solve (6) for D, given estimates of the yield M_i and the deposition epoch $t_{\rm SN}$, as determined by the depth of the supernova layer in the crust:

$$D = e^{-t_{\rm SN}/2\tau_i} \sqrt{\frac{f_i M_i}{16\pi A_i m_p N_i^{\rm obs}}} \tag{7}$$

where we have allowed for the reduced uptake as in (3). If one can deduce the supernova depositions of *two* radioisotopes i and j (where $\tau_i < \tau_j$), then one can use (6) with the combination the yields and the observed N_i and N_j to get not only D but also an independent estimate of t, as follows:

$$t_{\rm SN} = \frac{1}{\tau_i^{-1} - \tau_j^{-1}}\ \ln\left(\frac{A_j}{A_i}\,\frac{f_i}{f_j}\,\frac{N_j^{\rm obs}}{N_i^{\rm obs}}\,\frac{M_i}{M_j}\right) \tag{8}$$

This value is derived independently of the value of t inferred from the depth of the supernova-enhanced layer in the crust. The two values can thus be compared as a consistency check.

For the estimates below, we adopt the supernova yields from Woosley & Weaver (1995), one of the most extensive studies to date of supernova nucleosynthesis. Woosley & Weaver tabulate isotopic yields for nuclei with $A < 66$ over a range in progenitor masses and progenitor metallicity. Since the putative supernova would have occurred close to the Sun, we adopt the yields for solar metallicity. We note that, whilst the ^{53}Mn yield is expected to grow as a fairly smooth function of the progenitor mass, the ^{60}Fe yields are not. Consequently, the ^{53}Mn/^{60}Fe ratio varies widely and non-monotonically. The maximum is $^{53}\mathrm{Mn}/^{60}\mathrm{Fe} \simeq 20$ at $20 M_\odot$, and the minimum is $^{53}\mathrm{Mn}/^{60}\mathrm{Fe} \simeq 0.6$ at $13 M_\odot$. This introduces an additional uncertainty, since the mass of the nearby supernova is unknown. The initial mass function favors stars in the $11 - 20 M_\odot$ range, whose ^{53}Mn/^{60}Fe ratios span this range. We adopt the fiducial yield $M_{60} = 10^{-5} M_\odot$, corresponding to an intermediate value, recognizing that this is clearly somewhat uncertain.

3.1. Backgrounds

There are several potential contributions to the background. (1) Cosmogenic production, namely the spallative production of radioisotopes due to the steady cosmic-ray flux into the earth's atmosphere, was discussed in detail in Ellis, Fields & Schramm. We have repeated that analysis using the cross section for ^{60}Fe production via spallation in $p + {}^{84}$Kr, as reported in Knie et al. (1998). We agree with these authors that the ^{60}Fe from this source is several orders of magnitude below the observations. (2) A related source is *in situ* production, via the penetrating muon and neutron flux. We have estimated thus using the calculations by Lal & Peters (1967), and find that this source is negligibly small. (3) In the absence of a strong cosmogenic component, the dominant contribution to the background of both elements is the influx of extraterrestrial material, e.g., dust and meteorites, onto the earth. This material has been exposed to cosmic rays en route, and thus also contains the resulting spallogenic species at some level.

To compute the radioisotope contribution of infalling material, one must first determine the present rate J of meteoric mass accretion onto the earth. This quantity is difficult to measure, and past estimates have spanned a full six orders of magnitude, as seen in the tabulation of Peucker & Ehrenbrink (1996). However, recent measurements using different techniques have showed a convergence. Love & Brownlee (1993) have inferred the micrometeor ($\lesssim 10^{-4}$ g) mass spectrum and flux from the cratering patterns on the exposed surfaces of the Long Duration Exposure Facility satellite, and have reported a total accretion rate of $J = (4 \pm 2) \times 10^{10}\,\mathrm{g\,yr^{-1}}$ due to micrometeor infall. Love & Brownlee report that these objects have a mass spectrum which peaks around 1.5×10^{-5} g, corresponding to a diameter $\sim 200\,\mu$m, and have an infall rate which probably dominates the mass accretion on short timescales, with large (multi-ton) impacts possibly contributing a similar net influx on longer timescales. An independent measure of extraterrestrial dust accretion comes from the analysis of osmium concentrations and isotopic ratios in oceanic sediments. Recent inferred accretion rates of $(3.7 \pm 1.3) \times 10^{10}\,\mathrm{g\,yr^{-1}}$ from Peucker & Ehrenbrink (1996), and of $(4.9 - 5.6) \times 10^{10}\,\mathrm{g\,yr^{-1}}$ from Esser & Turekian (1988) agree with each other and with the Love & Brownlee result. We adopt a fiducial rate of $J = 4 \times 10^{10}\,\mathrm{g\,yr^{-1}}$, which we expect to be accurate to within 50%.

With the meteor accretion rate in hand, we now estimate the cosmogenic background by adopting the following simplified picture. In general, some fraction of the infalling material does not impact the earth directly as a meteorite, but is mixed into the atmosphere. This "well-mixed" fraction includes all of the smallest bodies (micrometeorites), and the portion of the larger bodies which is vaporized during the descent[1]. Since the accretion rate includes micrometeorites and dust, we assume that all such material is indeed well-mixed. We further assume that it is deposited isotropically on the surface of the earth. The total isotropic mass flux of incoming material is thus

$$\dot{\Sigma} = \frac{J}{4\pi R_\oplus^2} \tag{9}$$

If the average mass fraction of radioisotope i in the well-mixed infalling material is X_i, then the isotropic mass flux of i is just $\dot{\Sigma}_i = X_i\dot{\Sigma}$, and the number flux of i is

$$\begin{aligned} \Phi_i &= \frac{X_i\dot{\Sigma}}{A_i m_p} \\ &= 4.7 \times 10^{21}\ \frac{X_i}{A_i}\ \mathrm{atoms\ cm^{-2}\ \ Myr^{-1}}\ \left(\frac{J}{4 \times 10^{10}\ \ \mathrm{g\ yr^{-1}}}\right) \end{aligned} \tag{10}$$

The problem now reduces to finding X_i.

For ^{53}Mn, we use the results of Michel et al. (1991), who calculate the production of cosmogenic nuclides in meteoroids by cosmic-ray protons. These calculations are tabulated in Michel et al. (1991) for different kinds of meteoroids as functions of depth and size. We use the zero-depth values, since these correspond to the smallest and most common objects. Michel et al. express their results in terms of the specific activity Γ_i, i.e., the decay rate per unit mass of iron. Finally, we take the infalling material to have the iron mass fraction $X_{\mathrm{Fe}} = 0.19$, as found in C1 carbonaceous chondrites (Anders & Grevesse 1989). Then, in a meteorite with such a mass faction of iron, we have $X_i = m_i\tau_i\Gamma_i X_{\mathrm{Fe}}$, and so

$$X_{53} = 1.9 \times 10^{-11}\ \left(\frac{X_{\mathrm{Fe}}}{0.19}\right)\ \left(\frac{\Gamma_{53}}{400\,\mathrm{dpm\,kg\,Fe^{-1}}}\right) \tag{11}$$

Using this, we estimate a background flux of ^{53}Mn of

$$\Phi_{53} = 1.7 \times 10^9\ \mathrm{atoms\ cm^{-2}\ \ Myr^{-1}} \tag{12}$$

For comparison, Bibron et al. (1974) report a measurement of ^{53}Mn in antarctic snow which implies

$$\Phi_{53}^{\mathrm{obs}} = (6.1 \pm 1.4) \times 10^9\ \mathrm{atoms\ cm^{-2}\ \ Myr^{-1}} \tag{13}$$

[1]The vaporized material comprises the outermost layers of the falling material. For the larger objects these are also the regions with the highest concentration of spallogenic material.

whereas Imamura et al. (1979) measured ^{53}Mn in ocean sediments and found

$$\Phi_{53}^{\rm obs} = (2.0 \pm 0.9) \times 10^9 \text{ atoms cm}^{-2} \text{ Myr}^{-1} \tag{14}$$

The differences in these results highlight the large systematic errors in these estimates. However, within these uncertainties, we find our estimate to be in good agreement with the data.

The ^{60}Fe background is lower because ^{60}Fe lies above the iron peak, thus reducing the abundance of the possible target nuclei. Because of this and the shorter lifetime of ^{60}Fe, the data on ^{60}Fe in meteors are much sparser, and we know of just two relevant results in the literature. Early work by Goel & Honda (1965) detected ^{60}Fe in the Odessa meteorite with a specific activity of $\Gamma_{60} = 0.9 \pm 0.2\,\text{dpm}\,\text{kg}^{-1}$, for a sample with 7% Ni and 91% Fe, or $\Gamma_{60}^{\rm Ni} = 13 \pm 3\,\text{dpm}\,\text{kg Ni}^{-1}$. This report can be used to make a background estimate, as we did for ^{53}Mn. Using the specific activity of Goel & Honda and a Ni mass fraction $X_{\rm Ni} = 0.011$, we would find an ^{60}Fe flux of

$$\Phi_{60} = 1.3 \times 10^6 \text{ atoms cm}^{-2} \text{ Myr}^{-1} \tag{15}$$

This can be compared with the value we obtain from the ^{60}Fe/^{53}Mn ratio reported by Knie et al. for the Dermbach meteorite, which implies that $\Gamma_{60}^{\rm Ni} = 1.2 \times 10^{-2}\Gamma_{53}^{\rm Fe}$. For our adopted $\Gamma_{53}^{\rm Fe}$, this gives $\Gamma_{60}^{\rm Ni} = 5\,\text{dpm}\,\text{kg Ni}^{-1}$, and

$$\Phi_{60} = 0.5 \times 10^6 \text{ atoms cm}^{-2} \text{ Myr}^{-1} \tag{16}$$

In order to compare with the levels measured by Knie et al. in the ferromanganese crust, one must reduce the total ^{60}Fe flux by the uptake factor $f_{60} \sim 1/100$ discussed earlier (3). Thus the expected background ^{60}Fe is at least two orders of magnitude smaller that the observed level in the crust.

Knie et al. argue, however, that the ^{53}Mn and ^{60}Fe interstellar cosmogenic production mechanisms differ significantly. Namely, they argue that while ^{53}Mn comes primarily from spallation of Fe nuclei by high-energy Galactic cosmic rays, ^{60}Fe derives mostly from reactions on Ni induced by secondary neutrons. These secondary neutrons would be more abundant in the interiors of large meteors than in micrometeors or interstellar dust. In the absence of secondary neutrons, the ^{60}Fe production by protons alone is much smaller, leading to a lower specific activity Γ_{60} and finally a lower flux on earth. This scenario can be tested experimentally, by measuring the ^{60}Fe depth profile in meteorites.

An effect omitted from this simple calculation of the meteoritic background is that, if a nearby supernova occurs, it leads to an enhanced cosmic-ray flux not only on the earth, but also in the entire solar system, including, e.g., the material which falls as meteorites. Thus, one expects the meteoritic "background" to in fact include also some supernova "signal," and thus to undergo an increase which lasts for a timescale of order the species' lifetime. For the present data, this is not a serious issue. The enhanced cosmic-ray flux lasts for at most a few kyr, whereas the meteoritic sources average over several Myr, so the increase in the measured fluence for any given layer is only perceptible if the cosmic-ray flux enhancement is much larger than expected: the needed increase is a factor $\sim 10^3$, which is about an order of magnitude more than expected. However, if the signal could be measured with a much finer time resolution of order $10 - 100$ kyr, then this effect could be significant. At any rate, this discussion points up the advantage of measuring ^{53}Mn content in layers *prior* to the alleged supernova event, which should not show any supernova-related enchancement.

3.2. Distance and Epoch of the Putative Supernova

A crucial problem for any attempt to estimate these parameters is that the observed signals are present in all layers for both isotopes. We assume that the ^{60}Fe signal is real and not due to background, but not necessarily the ^{53}Mn signal. Even so, any deposition mechanism should be able to accommodate the continuous, rather than punctuated and isolated, nature of the signal.

We thus consider two possible scenarios.

1. As suggested by Knie et al., a continuous ^{60}Fe signal could arise from residual contamination due to the nearby supernova. Knie et al. note that this could contaminate the local interstellar medium, in particular contaminating dust in the local interstellar medium which could enter the solar cavity and fall onto the earth. Also, the cosmic-ray flux would irradiate metoric and cometary material in the solar cavity, leading to enhanced ^{60}Fe and ^{53}Mn production. Both processes lead to a ^{60}Fe flux which has an abrupt onset but is continuous until the ^{60}Fe is extinct. Until it is extinct, the present-day ^{60}Fe levels would be constant, assuming a constant dust accretion rate, since all of the ^{60}Fe was created at the same time, by the supernova event. This scenario is compatible with the observations.

2. Alternatively, it is possible that the ^{60}Fe signal is punctuated but mixed in the sample itself, e.g., by bioturbation. In this case, we should sum all of the signal, which we assume to have originated at the earliest time.

In fact, as we now see, these scenarios lead to similar predictions for D and $t_{\rm SN}$, as they share key aspects. In both, the ^{60}Fe was all produced by the putative supernova at the explosion epoch. Thus, the signal has decayed by the same factor $e^{-t_{\rm SN}/\tau}$, regardless of when the signal arrived on earth and was deposited on the crust. Thus, the signal in different crust layers should not be given a different correction for decay. Instead, the signals should all be added. This is what we do for both scenarios, for the following reasons. In scenario 1 with contamination of the local interstellar medium, the signal should have two components, an impulsive one received by the passage of the supernova blast through the solar system, and a continuous component derived from the solar system's accretion of interstellar material enriched by its passage. Both components are signal, and may not be well-resolved, depending on the relative strength, amplitude, and timescales of each. Thus, we sum the signals in all layers and take this to be a rough estimate of the fraction of material deposited on the earth. In scenario 2 we posit that the signal is mixed across layers. Thus, even if we assume that the deposition of material on the earth is only impulsive, the signal is smeared. To recover the original signal, we must again sum over the layers.

Thus, in both cases we take the signal to be

$$N_{60}^{\rm tot} = \sum_{\ell} N_{60}^{\oplus}(\Delta t_{\ell}) \sim 5 \times 10^{6} \ \text{atoms cm}^{-2} \tag{17}$$

Since only the ^{60}Fe is taken as signal, we need to know one of D or $t_{\rm SN}$ to get the other. An accurate estimate of either is impossible with the available data, but different assumptions enable us to make non-trivial limits and estimates, as seen in Fig. 1 and described in the following paragraphs.

The data of Knie et al. in each time period are shown in Fig. 1 together with their statistical error bars. As we have argued above, the sum $N_i^{\rm tot}$ is the appropriate measure of the total signal, and this is plotted as a vertical error bar for ^{60}Fe and ^{53}Mn on the right-hand sides of the two panels. The dashed lines also indicate the ranges favored for the possible signals.

In terms of our fiducial values, (7) now reads

$$D = 29 \ e^{-t_{\rm SN}/2\tau_{60}} \ \text{pc} \tag{18}$$

which we may use to derive constraints on the supernova distance and epoch. The maximum possible distance comes if the supernova happened "yesterday", which is possible only in the mixing scenario. In this case, $t_{\rm SN}/\tau_{60} \sim 0$, and we have a maximum distance of

$$D \lesssim D_{\rm max} = 30 \ \text{pc} \tag{19}$$

Interestingly, this distance happens to lie just within the Ellis, Fields, & Schramm (1996) estimate of the maximum distance at which a supernova might deposit its ejecta. Whilst the precision of the numerical agreement is accidental, and subject to the numerous uncertainties we have described, it is both amusing and intriguing that the two are so close. The upper (lower) solid curve in the top panel of Fig. 1 illustrates the signal expected from a supernova exploding at a distance of 10 (30) pc as a function of the time at which it exploded. As described in §2, the astrophysical predictions have been corrected for the reduced uptake via (3) with $f_{60} = 0.01$. We note that this distance constraint comes about by combining disparate information about supernova ejecta and observed surface densities. We find it both remarkable and encouraging that these numbers combine to give a distance limit that is not only of the right order of magnitude, but indeed jibes neatly with upper limit suggested by Ellis, Fields, & Schramm (1996).

A different consideration leads to another constraint which limits the epoch of the blast in both scenarios. Since the putative supernova apparently did not cause a catastrophic mass extinction, we require the distance to be larger than the Ellis & Schramm (1995) maximum killer radius: $D > 10$ pc, which gives

$$t_{\rm SN} \leq 4.6 \ \text{Myr BP} \tag{20}$$

as seen in Fig. 1. Thus, even without identifying a crust layer with the epoch of the ^{60}Fe deposition, we can already limit the distance to 10 pc $\lesssim D \lesssim$ 30 pc and the epoch to $t_{\rm SN} \lesssim 5$ Myr BP. The time constraints are not surprising, given that the very existence of the ^{60}Fe essentially demands that one place the putative supernova event within the past few ^{60}Fe lifetimes.

The result (20) raises an issue of self-consistency, since $t_{\rm SN}$ is so small as to be inconsistent with the age of the lowest (i.e., oldest) crust layer, $5.9 - 13.4$ Myr BP. This poses a problem in scenario 1, which predicts that no signal should appear before the explosion. One can resolve this issue in two ways. On the one hand, we can weaken the $t_{\rm SN}$ limits by taking a more conservative $2-\sigma$ lower limit on the summed signal. In this case, the age constraint rises to 5.9 Myr BP, just at the limit of the lowest layer's age. On the other hand, we note that only two events were detected in the lowest layer, with a possible instrumental background of one event, though Knie et al. argue that both events might be real and thus have not made any subtraction. If one regards the events in the oldest layers as background, one should remove this layer's contribution to the sum (17). In this case, the time constraint to now gives a consistent limit of $t_{\rm SN} \leq 5.4$ Gyr BP.

We have so far used only the ^{60}Fe data, assuming that the observed ^{53}Mn is background, but this assumption is subject to challenge. Whilst the detected flux is roughly consistent with the expected background, our estimate is sufficiently uncertain that it is worth examining the alternative. Indeed, self-consistency demands that we estimate the expected ^{53}Mn signal, which may be obtained directly from ^{53}Mn/^{60}Fe ratio. The vertical error bar and dashed lines in the lower panel of Fig. 1 represent the sum of the ^{53}Mn data. The curves in this panel represent the astrophysical predictions for supernovae at distances of 10 or 30 pc as before, assuming $f_{53} = 0.05$ and ^{53}Mn/^{60}Fe $= 20$. As noted above, this ratio is unfortunately uncertain, but we expect ^{53}Mn/^{60}Fe $\lesssim 20$. If the true value lies at the high end of this range, i.e., if $m_{\rm SN} \simeq 20 M_\odot$, then the observed ^{53}Mn might also be signal, as seen in the lower panel of Fig. 1. In this case, the ^{53}Mn signal can no longer be used to estimate the reduced Mn uptake, so we lose our ability to estimate f_{53} and f_{60}. On the other hand, if we interpret both radioisotopes as signal, we can derive the supernova epoch. Taking the net ^{53}Mn surface density as pure signal and using (8), we have

$$t_{\rm SN} = 4.3\,{\rm Myr}\ \ {\rm BP} \tag{21}$$

as also seen in Fig. 1, and in good agreement with the range estimated above. In terms of the (now unknown) reduced uptake for ^{53}Mn, this would imply a supernova distance of $D = 48 f_{53}^{1/2}$ pc, or $D \lesssim 50$ pc for any $f_{53} < 1$.

It is already a new statement about supernova nucleosynthesis if the ^{60}Fe in the ferromanganese crust data indeed has a supernova origin. This isotope has long been predicted to come from supernovae. In recent calculations, Woosley & Weaver (1995) note that ^{60}Fe is made in presupernova via *s*-process He burning, and explosively at the base of the O and Si burning shells. Observationally, there is meteoric evidence that live ^{60}Fe was present in the protosolar nebula, perhaps due to a supernova explosion soon before the formation of the solar system (Shukolyukov & Lugmair 1992, 1993). Furthermore, ^{60}Fe has received particular attention because its decay through ^{60}Co to ^{60}Ni is accompanied by the emission of 1.17 and 1.33 MeV γ rays, making it a target for search by γ-ray telescopes. Timmes et al. (1995) noted that the expected γ-ray signal should spatially trace that of ^{26}Al. They calculated the flux levels, and found them to be just below the sensitivity of the Compton Gamma-Ray Observatory. However, ^{60}Fe should be visible by the upcoming INTEGRAL γ-ray satellite. Until seen in γ rays, the data discussed here could be the strongest available indication of a supernova origin for ^{60}Fe.

The observation of additional radioisotopes (Ellis, Fields, & Schramm 1996) would not only help constrain the distance, but would also allow one to use the various radioisotope measurements as a telescope which provides information about the supernova nucleosynthesis processes. Therefore, we urge more searches, both of ferromanganese crusts like the one reported (for repeatability and confirmation that the effect is global), as well as other materials and particularly other radioisotopes which would help confirm the extraterrestrial origin and add to the constraints on the timing, distance, and mass of the putative explosion. Candidate species are those which are expected to be made copiously in supernovae and have lifetimes comparable to the $\sim 10\,\mathrm{Myr}$ timescale considered. Promising candidates include ^{10}Be, ^{129}I, and ^{146}Sm. Note that ^{10}Be has a half-life $t_{1/2} = 1.51\,\mathrm{Myr}$ which is equal to that of ^{60}Fe, within errors. Thus, the ^{10}Be/^{60}Fe ratio due to a nearby supernova should remain constant over time, providing a consistency check. Also, ^{10}Be will have contributions from enhanced cosmogenic production as well as any possible supernova origin. The other isotopes of note, ^{129}I ($t_{1/2} = 15.7\,\mathrm{Myr}$) and ^{146}Sm ($t_{1/2} = 10.3\,\mathrm{Myr}$), have longer lifetimes, and thus can probe earlier epochs. This could again allow for a cross-check: if ^{129}I and ^{146}Sm are enhanced along with ^{60}Fe, they should drop off in material which dates prior to the explosion event.

To get a feel for the likelihood of the putative nearby supernova, we estimate the expected rate for an explosion occurring with a given distance. Following Shklovsky (1968), the average rate λ of supernovae within a distance D is just the total Galactic rate $\mathcal{R}_{\mathrm{SN}}$, times the volume fraction: $\lambda = (4D^3/3R^2h)\,\mathcal{R}_{\mathrm{SN}}$, where R is the disk radius and h the scale height. Using $R = 20$ kpc, $h =$ 100 pc, and the possibly optimistic estimate $\mathcal{R}_{\mathrm{SN}} = 3 \times 10^{-2}\,\mathrm{yr}^{-1}$, we get $\lambda \sim 1\,\mathrm{Gyr}^{-1}\,(D/10\,\mathrm{pc})^3$. Thus an explosion at a distance of 30 pc should have a mean recurrence time of 100 Myr. This is at least an order of magnitude larger than the timescale suggested by the ^{60}Fe data, which suggests that either the supernova was unusually recent, or that the rate has been grossly underestimated. In this connection, we note that a recent and nearby supernova remnant has been identified by Aschenbach (1998). At an estimated distance of about 200 pc, which is too distant to have any effect of the type we discuss, but its age of about 700 yr (Iyudin et al. 1998) does suggest that the rate of nearby supernovae could be higher than the above estimate.

Moreover, we note that the expected supernova rate is enhanced during the passage of the earth through spiral arms (Shapley 1921; Hoyle & Lyttleton 1939; Clark, McCrea, & Stephenson 1977). This occurs every 10^8 yr or so, and it would be interesting to seek evidence for any possible correlation with past extinctions. It seems that we are now approaching or just entering the Orion arm, so that an elevated supernova rate is possible.

4. Impact on the Biosphere

Potential implications of a nearby supernova explosion for earth's biosphere have been considered by a number of authors (Ruderman 1974; Ellis & Schramm 1995; Ellis, Fields, & Schramm 1996), and recent work has suggested that the most important effects might be induced by cosmic rays. In particular, their possible role in destroying the earth's ozone layer and opening the biosphere up to irradiation by solar ultraviolet radiation has been emphasized (Ellis & Schramm 1995; Ellis, Fields, & Schramm 1996). The energetic radiation from supernovae contains two components: a neutral one due to γ rays, which has been estimated to have a fluence

$$\phi_\gamma \sim 6.6 \times 10^5 \left(\frac{10}{D}\right)^2 \mathrm{erg\,cm^{-2}} \tag{22}$$

for about a year, where here and subsequently D is understood to be in units of pc, and a charged component whose flux has been estimated to have a fluence

$$\phi_c \sim 7.4 \times 10^6 \left(\frac{10}{D}\right) \mathrm{erg\ cm^{-2}} \tag{23}$$

for about $3\,D^2$ yr, to be compared with the ambient flux of $9 \times 10^4\,\mathrm{erg\,cm^{-2}yr^{-1}}$. We see that the ambient flux would be doubled if $D \sim 30$ pc, with considerable uncertainties, and could be considerably greater if $D \sim 20$ pc, which cannot be excluded. These enhanced fluxes are not thought likely to be directly dangerous to life.

However, it has been argued (Ruderman 1974; Ellis & Schramm 1995; Ellis, Fields, & Schramm 1996) that this ionizing radiation should produce NO in the stratosphere, making a contribution

$$y_{cr} \sim 88 \left(\frac{10}{D}\right)^2 \tag{24}$$

to the NO abundance in parts per 10^9. This is in turn estimated to deplete the ozone abundance by a factor

$$F_O = \frac{\sqrt{16 + 9X^2} - 3X}{2} \tag{25}$$

where $X = (3 + y_{cr})/3$ is the factor of enhancement in the abundance of NO. In the case of a supernova at 30 pc, we would estimate $F_O \sim 0.33$. The factor by which the penetrating flux of solar ultraviolet radiation at the earth's surface is increased by this ozone depletion is approximately $f^{F_O - 1}$, where f is the fraction of the solar ultraviolet flux that normally reaches the surface. In the case of radiation with a wavelength of 2500 Å, which is effective for killing *Escherichia Coli* bacteria and producing erythema (sunburn), $f \sim 10^{-40}$ normally. We estimate that supernova at 30 pc might increase this by some 27 orders of magnitude, for a period measured in thousands of years. Clearly these estimates are very unreliable, but they serve as a warning that the effects of such a supernova may not be negligible.

All the biosphere is dependent on photosynthesizing organisms at the bottom of both the terrestrial and marine food chains. Terrestrial photosynthesis is most effective for red light with a wavelength $\sim$ 570 nm, and we do not know of any detailed studies how it might be impacted by enhanced solar ultraviolet radiation. On the other hand, carotenoids in phytoplankton shift their most sensitive wavelength towards the blue. This might provide a mechanism for an amplification of the possible effect on marine ecology relative to terrestrial ecology. The effect of enhanced solar ultraviolet radiation on marine photosynthesis by phytoplankton has in fact been studied in connection with the ozone hole in the Antarctic, and a decline in the rate of photosynthesis by phytoplankton exposed in plastic bags has been demonstrated (Smith et al. 1992), although this needs to be understood in the context of other effects such as vertical mixing and cloudiness (Neale, Davis, & Cullen 1998).

It is natural to ask at this point whether any significant extinction events are known to have occurred within the past 10 Myr or so during which the apparent excess of ^{60}Fe may have been deposited. Indeed, there is evidence for a couple of minor extinctions: one during the middle Miocene, about 13 Myr ago, and one of lesser significance during the Pliocene, about 3 Myr ago (Sepkoski 1986). Impacts on marine animal families near the bottom of the food chain have been noted, including zooplankton such as tropical foraminifers (which eat phytoplankton), bivalves, gastropods and echinoids (whose diets include plankton and debris). This is exactly the pattern that might be expected from a major insult to marine photosynthesis. It is interesting to note that the stability of phytoplankton community structure over 200 kyr has been demonstrated using deep-ocean sediments (Schubert et al. 1998), and it would be valuable to extend such studies to longer periods. It would be fascinating to devise a single experiment that could correlate directly possible isotope and phytoplankton signatures of a supernova event [2].

Many other possible causes of such an insult should be considered, including volcanism and meteor impact(s), and we would like to mention another possibility that could also be linked to a nearby supernova explosion. A strong correlation has been observed (Friis-Christensen & Lassen 1991; Svensmark & Friis-Christensen 1997; Svensmark 1997) between solar activity (particularly the solar sunspot cycle) and the earth's cloud cover. It is thought that cosmic rays may help seed cloud formation, and it has been suggested that the correlation with the sunspot cycle might be due to the known modulation of the cosmic-ray flux during the solar cycle (Ney 1959), which is due to variations in the solar wind. Increased cloud cover is expected to reduce the earth's surface temperature (Hartmann 1993), and it has been conjectured that the lower global temperatures three centuries ago might be related to the different level of sunspot activity at that time [3]. We remark that the large increase in the cosmic ray flux that we estimate from a nearby supernova explosion might seed a large increase in the cloud cover, possibly triggering a "cosmic-ray winter"

[2]We observe in passing that a weak correlation has been observed between magnetic field reversals and mass extinctions (Raup 1985). We note that an enhanced cosmic-ray flux is one consequence of such a reversal.

[3]Interestingly, William Herschel noted two centuries ago that wheat prices were anticorrelated with sunspot numbers.

lasting for thousands of years [4]. Indications from recent solar cycles are that variations in the cosmic-ray flux by about 20% might be correlated with fractional changes of the cloud cover by about 3%, corresponding in turn to variations in the mean earth temperature by about 0.4 K (Kirkby 1998). This is a very speculative possibility, since there are considerable variations in the flux of cosmic rays at different energies and latitudes, and their efficiency for seeding clouds is only guessed from a statistical analysis. Also, the ensuing impact on the environment would be very complex, though no obvious mechanism that would enhance the effect on marine life comes immediately to mind. However, we do at least note that accelerator experiments to probe the possible seeding of clouds by cosmic rays are now being considered (Kirkby 1998).

5. Conclusions

We have discussed in this paper the implications of the possible anomalous ^{60}Fe signature of a nearby supernova explosion reported recently by Knie et al. (1998). We re-emphasize that the interpretation of this effect requires confirmation. This could be addressed by searching for anomalies in other radioisotopes as suggested here and in Ellis, Fields & Schramm (1996), by checking that the ^{60}Fe background is low as argued here and in Knie et al. (1998), by verifying that the ^{60}Fe enhancement is global, and by checking that the ^{60}Fe signal is absent in earlier ferromanganese layers.

Nevertheless, if the signal is real, it is the first direct evidence for the supernova production of ^{60}Fe, and may be used to constrain the possible distance and epoch of the putative supernova. We find that a distance of about 30 pc is consistent with the magnitude of the ^{60}Fe signal, and that it should have occurred about 4 Myr ago. If the supernova origin of the observed ^{60}Fe is confirmed, this opens up a whole new era of supernova studies using deep-ocean sediments as telescopes. We draw particular attention to the interest of searching for ^{10}Be, ^{129}I, and ^{146}Sm as well as ^{53}Mn and ^{60}Fe.

Finally, we have been encouraged by the report of Knie et al. to review the possible impact of a nearby supernova explosion on the biosphere. In this connection, we recall that a couple of mini-extinctions have been reported within the past 10 Myr or so, during the Middle Miocene and Pliocene. It would be interesting to investigate whether either of these may be correlated with a supernova event. We have noted in passing that an enhancement of the cosmic-ray flux, such as that accompanying a nearby supernova explosion, might increase the global cloud cover. It remains to be seen whether this might induce significant climate change such as, in an extreme case, a "cosmic-ray winter". If the ^{60}Fe signal reported by Knie et al. is confirmed, such speculation would become more compelling.

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[4] Increasing the cloud cover might also provide a mechanism for reversals of the terrestrial magnetic field to trigger global cooling, since field reduction during a reversal could enable a higher cosmic-ray flux to reach the earth's upper atmosphere.

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FIGURE CAPTION

1. The upper (lower) panel compares the data of Knie et al. (1998) with our predictions for the surface density of ^{60}Fe (^{53}Mn). The data in each time period are plotted with vertical statistical error bars, and their sums are indicated by the error bars on the right-hand sides of the panels and the horizontal dashed lines. The upper (lower) solid curves are the astrophysical predictions assuming a supernova explosion at a distance of 10 (30) pc. To compare with the data, these predicted global surface densities have been corrected downward by reduced uptake factors (3), using the Knie et al. values $f_{60} = 1/100$ and $f_{53} = 1/20$.